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Movement of diagonal resistivity in fractional quantum Hall effect via periodic modulation of magnetic field strength

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Abstract. We examine the effect induced by periodic modulation of magnetic field strength in the fractional quantum Hall effect (FQHE). The classical Coulomb energy of the fractional quantum Hall (FQH) state is linearly dependent on $1/\nu$, where ν represents the fractional filling factor. This energy varies continuously with ν. The residual Coulomb interactions produce quantum transitions. Then, the binding energy via the transitions yields an energy gap for specific fractional filling factors and no gap for the other fractional filling factors. The strength of the static magnetic field is fixed to yield an FQH state with gap energy. Then a periodic magnetic modulation is added to the system. Its resultant diagonal resistivity depends upon the oscillation frequency of the magnetic modulation. Examination of that dependence shows that the resistivity varies drastically at some frequency value, which can be evaluated for several fractional filling factors. These phenomena are strongly dependent upon the energy spectra of FQH states.

1. Introduction

Many investigations have been made of the fractional quantum Hall effect (FQHE) [1–11]. Furthermore, many physicists have theoretically investigated FQHE [1–5]. Recently, precise experiments have been carried out in ultra-high-mobility samples. Many local minima of diagonal resistivity ρ_{xx} were discovered at filling factors ν=3/8, 3/10, 4/11, 4/13, 5/13, 5/17, 6/17, and so on [6, 7]. It is difficult to explain the stability of these states using traditional theories. Accordingly, many theorists have proposed their extended models, for example, Wojs et al. [8], Smet [9], and Pashitskii [10]. Therefore, many interesting problems related to FQHE remain.

We propose a new experiment for the fractional quantum Hall effect in this paper as follows: we consider the phenomenon by which an oscillating magnetic field is applied to a fractional quantum Hall state in addition to the static magnetic field. In this case, the diagonal resistance R_{xx} depends upon the frequency of the oscillating magnetic field. For this study, we examine this dependence.

2. Energy structure of Fractional Quantum Hall States

Experimental data show that several FQH states are extremely stable for specific fractional filling factors. The experimental value of Hall resistance $R_H(\nu)$ is precisely equal to $h/(e^2\nu)$ for the filling factors ν =2/3, 1/3, 1/5, 2/5, 3/5, and so on, where h is Planck's constant and e is the electron charge.

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The deviation $\left(R_H(\nu)-h/(e^2\nu)\right)/R_H(\nu)$ is about 3×10^{-5} for $\nu=2/3$ and about 2.3×10^{-4} for $\nu=2/5$, as described in the literature [12]. This precise confinement of Hall resistance shows the existence of an energy gap for these filling factors. Few investigations have addressed the curve of electron energy versus the filling factor [3, 11, 13]. One example is reference [13], where the energy per electron $\varepsilon(\nu)$ versus filling factor ν has an energy gap, as in figure 1.

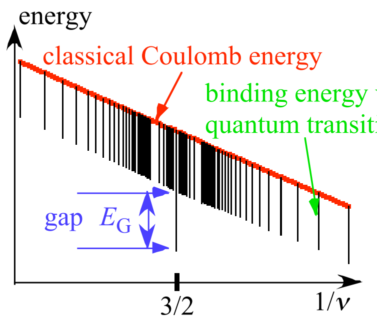

Figure 1. Energy gap near $\nu=2/3$

This energy gap produces the precise confinement of Hall resistance as follows. The energy per electron $\varepsilon(\nu)$ is the sum of Landau energy, classical Coulomb energy, and quantum transition energy [11]. The Landau energy is the eigenenergy of a single electron, neglecting Coulomb interaction; it depends upon magnetic field strength *B* as $\hbar eB/(2m)$, where $\hbar$ is $h/(2\pi)$, and *m* is the electron mass. Therefore, the energy $\varepsilon(\nu)$ increases linearly according to increasing magnetic field strength *B*. We draw schematic figures of the energy spectrum near $\nu=2/3$ for three values of *B* in figure 2, where μ is the chemical potential per electron.

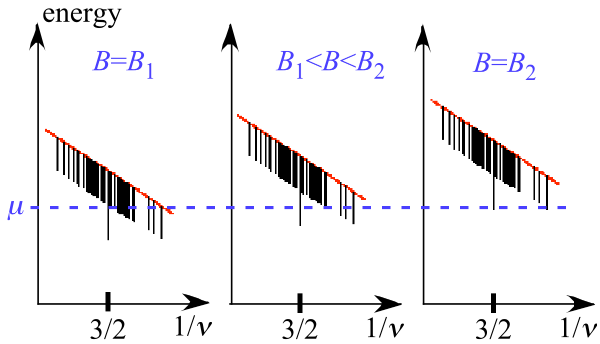

Figure 2. Energy per electron for three value of magnetic field

As shown in figure 2, the electron state with $\nu=2/3$ has an energy less than μ for $B_1<B<B_2$, but all electron states in $\nu>2/3$ have energy values greater than μ for $B_1<B<B_2$. Consequently, only the state with $\nu=2/3$ is filled with electron at a low temperature because of Fermi degeneracy. This property produces the precise confinement of Hall resistance R_{xy} and produces vanishing of diagonal resistance R_{xx} for $B_1<B<B_2$. The diagonal resistance versus magnetic field strength has been measured in many experiments, one of which is described in the literature [6]. The data near $\nu=2/3$ are shown in figure 3.

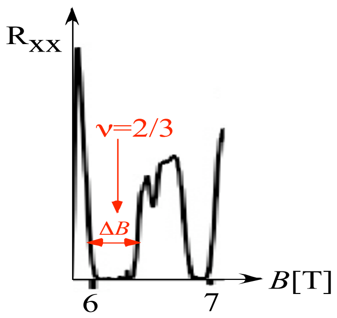

Figure 3. Experimental results of diagonal resistance R_{xx} near $\nu = 2/3$ in reference [6]

Figure 3 shows that the values of B_1 and B_2 are

$$B_1 \approx 6[\mathrm{T}],\ B_2 \approx 6.3[\mathrm{T}] \text{ and } \Delta B = 0.3[\mathrm{T}] \qquad (1)$$

for the quantum Hall device used in an earlier study [6]. According to the previous explanation for figure 2, the gap energy $E_G(\nu)$ of this device is given as

$$E_G(\nu) = \hbar e(B_2 - B_1)/(2m) \quad . \qquad (2)$$

Therefore, the numerical value is obtained as

$$E_G(2/3) \approx \hbar e(6.3 - 6)/(2m) \text{ for } \nu = 2/3 , \qquad (3)$$

which is derived from Eqs. (1) and (2).

3. New experiment

We consider a new experiment as:
(1) The strength of static magnetic field is fixed to maintain the FQH state with $\nu = 2/3$.
(2) A periodic magnetic modulation is applied to the system. The frequency value is f.
(3) The diagonal resistance R_{xx} is measured under changing of the frequency value f.
Then the value of R_{xx} probably depends upon the oscillation frequency f. The behaviour of R_{xx} versus f is predicted as illustrated in figure 4.

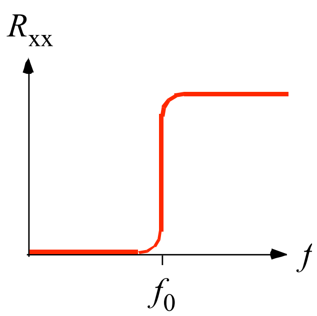

Figure 4. Dependence of diagonal resistance R_{xx} for variation of f

Herein, the value of f_0 is defined as

$$f_0 = E_G(\nu)/(2\pi\hbar) = e(B_2 - B_1)/(4\pi \ \ m) . \qquad (4)$$

The electrons at $\nu = 2/3$ cannot be excited in $fh < E_G$, as shown in Fig. 1. Accordingly, the diagonal resistance R_{xx} vanishes for $f < f_0$ at an ultra-low temperature. Electrons are excited when the frequency f becomes larger than f_0. Therein R_{xx} becomes very large. Consequently, the diagonal resistance value changes drastically near frequency f_0, as shown in figure 4.
The critical frequency f_0 is evaluated for the device used in a previous study [6].

$$f_0 \approx 1.602\times10^{-19}(0.3)\Big/\left(4\pi\ \ 9.109\times10^{-31}\right) \approx 4.2\times10^{9} \text{ for } \nu = 2/3 \qquad (5)$$

That is to say, f_0 is about 4.2 GHz at $\nu = 2/3$. For the other filling factors, this critical frequency becomes a different value, e.g.

$$f_0 \approx 1.7\times10^{9} \text{ for } \nu = 3/5. \qquad (6)$$

That is to say, f_0 is about 1.7 GHz at $\nu = 3/5$. These critical values for each filling factor depend upon the structure of a quantum Hall device. Nevertheless, the relation between f_0 and $\left(B_2 - B_1\right)$ holds, as demonstrated in Eq. (4).

4. Conclusion

We have described a new experiment by which the diagonal resistance is predicted to change drastically at a critical frequency at specific filling factors. Each critical frequency is related to the magnetic field width $\left(B_2 - B_1\right)$, as shown in Eq. (4). We can adopt a periodic modulation of electric current in a Hall device or an irradiation of electromagnetic wave if periodic modulation of the magnetic field is difficult to apply in experiments. These experiments will clarify new properties of the fractional quantum Hall effect.

5. References

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